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Field experience on solar electric power systems and their potential in Palestine

Marwan M. Mahmoud, Imad H. Ibrik *

Energy Research Centre, An-Najah National University, Nablus P.O. Box 721, West Bank, Palestine, Israel

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Abstract

Palestine has a large number of rural small villages far from the national electric grids. Electrical loads in such villages are mostly small and can be covered by means of photovoltaic (PV) generators, which are economically more feasible than extending the electric grid or using diesel electric generators. Since PV has been rarely used in Palestine, this paper is devoted to investigating the potential of PV applications in Palestine, identifying the barriers for prevalence of PV applications as in other countries and demonstrating the reliability and feasibility of utilizing PV systems by presenting the test results of a PV system by supplying a rural clinic with its power demands. A method for designing the PV power system respecting the local environmental conditions is presented in this paper. The results of the measurements carried out over two years verify the reliability of the applied method. The illustrated test results show how far the PV-power generation can be matched with load demands and state of battery charge even during periods of low solar radiation. This could be achieved by respecting the local weather parameters in the illustrated sizing method. Long term field experience in designing, testing and operation of PV projects outside Palestine is presented in this paper.

Keywords: Photovoltaic power generators; Solar electrification; Rural development; Renewable energy

* Corresponding author. Fax: +972-92383589.
E-mail address: iibrik@yahoo.com (I.H. Ibrik).

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Contents

1. Introduction

Even though the area of Palestine is relatively small, it has a large number of remote small villages as well as settlements that lack electricity services, and the probability of connecting them in the near future is very poor due to political circumstances. The daily energy demands in such villages are very low and vary in the range from 500 to 3000 W h per household. As is known, such electrical loads are appropriate to be covered by means of photovoltaic (PV) generators and especially in countries such as Palestine, where the daily solar radiation intensity exceeds 5 kW h/m^2 day. In fact, during the last two decades, PV had been widely used in many countries for electrification of rural areas [1]. In many cases, using PV is economically more feasible than generating power by diesel or extending the electric grid to loads [1]. Unfortunately, PV had been used rarely in Palestine even though the potential is high especially for the electrification of small villages, supplying of remote radiocommunication stations and water pumping systems from wells and springs [2]. Since the costs of fuel and electric energy in Palestine are extremely high (US$ 0.65/l diesel and US$ 0.22/kW h electricity), PV power should be more seriously considered for rural electrification. This paper presents a successful PV power system provided to a rural clinic in a small isolated village in Palestine. Measurements on this system have been carried out continuously for two years. The test results demonstrate the high reliability and performance of such systems, which encourage the widening of the utilization of PV technology in non-electrified Palestinian rural areas.

2. Photovoltaic applications in Palestine

In comparison with many countries, the number of PV applications in Palestine is very limited. Until now, the total installed PV peak power does not exceed 10 kW. The main reasons are summarized in the following:

- Occupation of Palestine by the Israeli military for 28 year during the period 1967–1995, when all developments in the energy sector were stopped.
- A variety of national organizations competing with each other to work in the energy field without any constructive coordination.
- Lack of realistic professional study on the potential of renewable energy applications in Palestine.
- Lack of national energy plan that considers the embracing of feasible renewable energy applications.
- Lack of concern by the energy planners and decision makers towards renewable energy applications due to deficiency of objective information.
- Lack of foreign financial resources allocated for the development of the renewable energy sector.

However, a considerable potential for PV applications in Palestine is available that relies on the following facts:

- High average of solar radiation intensity amounting to 5.4 kW h/m^2 day and sunshine hours of about 3000 h per year [2].
- Availability of a large number of rural villages, settlements and public utilities isolated from the electric grid that will not be connected to it in the near future.
- High fuel cost in Palestine that makes PV more feasible than diesel powered electric generators in supplying power to different applications in rural areas [2].

With respect to Palestinian conditions, the most feasible PV applications in rural areas are represented in supplying power for lighting, colour televisions, computers, refrigerators, clinic lab equipment, communication equipment and water pumps. As is known, operation of these appliances is most essential for the development of rural areas.

3. Photovoltaic power supply to an isolated clinic

Besides providing power to isolated single houses, electrification of small clinics in rural villages was the first PV application in Palestine. Due to the above-mentioned reasons, the number of PV powered clinics is limited to only seven clinics [2]. The PV power systems in these clinics are similar since the electrical appliances in them are also similar. To illustrate the performance and feasibility of these systems, we present here the design and test results of a PV power system.

3.1. System design

The electrical appliances used in the clinic are specified as follows:

- Five energy saving lamps (compact fluorescent lamps, CFL) each rated at 12 V DC/13 W.
- One refrigerator with 197 l capacity rated at 12 V DC/65 W.
- One colour TV rated at 12 V/45 W.
- Two medical analysing equipment rated at 12 V DC/25 W and 12 V DC/40 W.
- Two ventilators each rated at 12 V DC/15 W.

These appliances represent an electric load which is not continuously constant but varies seasonally according to change of ambient temperature, which affects the operation time of the refrigerator and ventilators. This means that the maximum and minimum loads are coincident with summer and winter months, respectively. Based on weather parameter measurements taken at the clinic site [3], the daily average of ambient temperature varies between 13.5 °C in January and 30 °C in July, while the absolute minimum and maximum coincide during the same months and amount to −1 and 49.2 °C, respectively. Depending on these data, the average daily load is estimated to vary between 1 and 1.9 kWh/day, while it amounts to 1.42 kWh/day on a yearly basis.

For such a small daily load, it is most appropriate to choose a PV system (without inverter) to deliver DC voltage and current to the load as illustrated in Fig. 1.

The system consists of a PV array converting the solar radiation falling on its surface into electric DC power, a storage battery, and a voltage regulator (VR) converting the DC voltage produced by the PV array into DC voltage with an appropriate value for charging the storage battery and a load. The VR is also necessary to protect the battery against deep discharging and overcharging, which usually shorten the lifetime of the battery. In addition, the system includes a data acquisition system to measure automatically the produced and consumed power beside the A h-input/output of the battery.

3.2. System sizing

Sizing the components of the PV system (Fig. 1) depends mainly on the daily energy load (E_{dl}), the annual daily average of solar radiation intensity on the project site (E_{ds}) and on the monthly distribution of temperature averages.

The total PV peak power (P_{pv}) required to cover the daily energy demands of the load is obtained as follows [4]:

$$P_{pv} = \frac{E_{dl} \times G_o}{\eta_{cr} \times E_{ds}} \times S_f \tag{1}$$

where $E_{dl} = 1420$ Wh/day, $E_{ds} = 5400$ Wh/day (average solar radiation intensity in Palestine), $G_o = 1000$ W/m^2 at $T_{amb} = 25$ °C (solar radiation intensity at standard conditions [5,6]), $\eta_{cr} = 0.94$ (efficiency of the selected battery charge regulator,

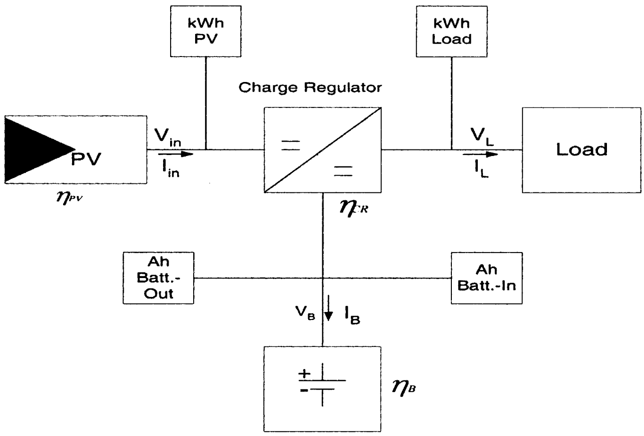

Fig. 1. PV power system supplying the clinic with DC power.

mostly higher than 92%), and S_f is the safety factor to compensate for wiring and resistive losses in the system, cloudy days and power loss due to the increase of PV cell temperature. For PV systems in Palestine, $S_f = 1.33\%$ is practically an appropriate value. Substituting these values in Eq. (1), we obtain:

$$P_{pv} = 372 \text{ W}_p \text{ (watt peak)}$$

3.2.1. Photovoltaic array

To build a PV array capable of providing this peak power, a polycrystalline silicon PV module type AEG PQ 10/40/01 of a gross area of $A_{pv} = 0.494$ rated at 12 V DC and a peak power of $P_{mpp} = 38.4$ W_p was found to be appropriate.

The number of necessary PV modules, N_{pv}, is obtained as:

$$N_{pv} = \frac{P_{pv}}{P_{mpp}} = 9.7 \tag{2}$$

(i.e. 10 PV modules will be necessary, which means consequently that $P_{pv} = 384$ W).

Fig. 2 illustrates the equivalent circuit of this module, while Fig. 3 illustrates the *IV* characteristic of this module measured under natural weather conditions. Applying Kirchhoff's current law on the equivalent circuit, we obtain the following equation for the *IV* characteristic [5]:

$$I = I_{ph} - I_o[\exp\frac{q}{AKT}(V + R_sI) - 1] - \frac{(V + R_sI)}{R_{sh}} \tag{3}$$

where I_o is the reverse saturation current, K is the Boltzman constant (1.38×10^{-23} W_s/K), T the temperature in kelvin ($= 273 +^\circ$ C), I_{ph} the light generated current, q the electron charge ($= 1.6 \times 10^{-19}$ A s), A the diode ideality factor,

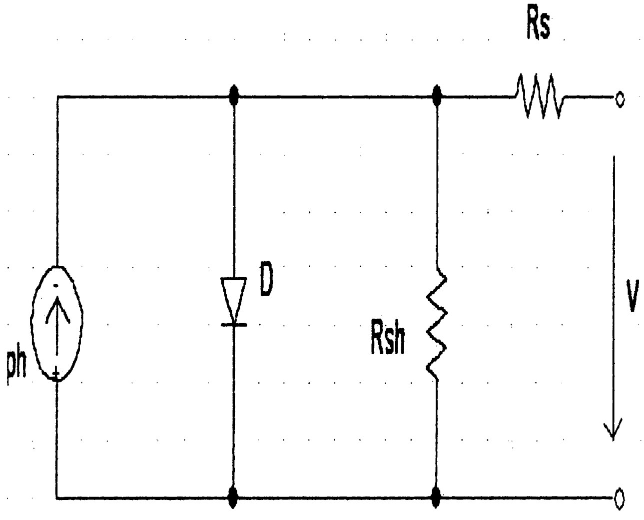

Fig. 2. Equivalent circuit of the polycrystalline PV module.

R_s the series resistance, R_{sh} the shunt resistance, V the terminal voltage and I the terminal current (load voltage and load current, respectively).

As the IV characteristic shows, the short circuit current is $I_{sc} = 2.5$ A, and the open circuit voltage is $V_{oc} = 22.4$, while the current and voltage at maximum power point (V_{mpp} and I_{mpp}) are 2.19 A and 17.5 V, respectively. The peak efficiency and fill factor of the PV module (η_{pv} and F_f, respectively) are the most important characteristic parameters and are computable from the IV characteristic

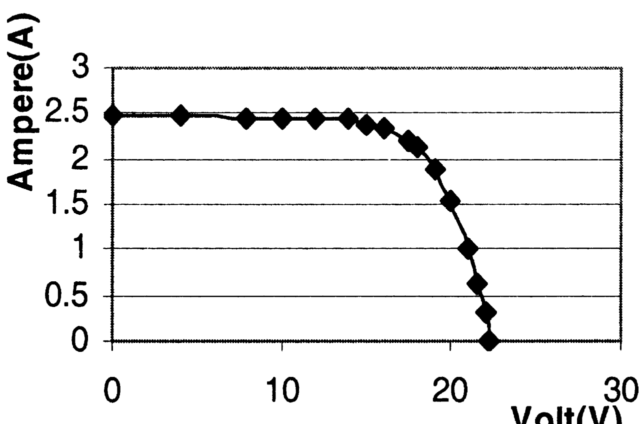

Fig. 3. IV characteristics of the PV module type: AEG PQ 10/40/01.

as follows [7]:

$$\eta_{pv} = \frac{V_{mpp} \times I_{mpp}}{G_o \times A_{pv}} \tag{4}$$

$$F_f = \frac{V_{mpp} \times I_{mpp}}{V_{oc} \times I_{sc}} \tag{5}$$

A nominal load voltage of 12 V DC was selected for this system. To fulfil this requirement, all 10 PV modules were connected in parallel. This means that at standard condition, I_{sc} and V_{oc} of the PV array are 25 A DC and 22.4 V DC, respectively. The PV modules were built on a hot galvanized steel structure facing south with a tilt angle (β) of 45° to the horizon according to latitude of the project site and variation of the solar altitude.

The solar radiation intensity on the surface on the PV array (G) is obtainable through the following relation [6]:

$$G = G_H \cos\beta \tag{6}$$

where G_H is the solar radiation intensity measured on a horizontal surface. The input solar power of the PV array P_{sin} is defined as:

$$P_{sin} = G \times A_{pv} \tag{7}$$

To secure an output voltage of the PV array which is always sufficient for charging the storage battery, it is necessary to consider the negative effect of increasing the ambient temperature on the PV cell temperature (T_c) and consequently on the output voltage and power. This effect is considered by the following equations [8]:

$$V_{OCT} = V_{OCO}[1 + h_V(T_c - 25\ ^\circ C)] \tag{8}$$

$$I_{SCT} = I_{SCO}[1 + h_I(T_c - 25\ ^\circ C)] \tag{9}$$

$$T_c = T_{amb} + \frac{NOCT - 20\ ^\circ C}{800\ W/m^2} \times G \tag{10}$$

where V_{OCT} and I_{SCT} are the open circuit voltage and short circuit current of the PV array at T_{amb}; V_{OCO} and I_{SCO} are the open circuit voltage and short circuit current of the PV array at standard conditions; h_V and h_I are the temperature coefficients for voltage and current (for a silicon solar cell $h_V = -3.7 \times 10^{-3}/^\circ C$ and $h_I = 6.4 \times 10^{-4}/^\circ C$) and NOCT is the nominal operating cell temperature at $G = 800\ W/m^2$, $T_{amp} = 20\ ^\circ C$ wind velocity $V_w = 1$ m/s, $I = 0$ and $V = V_{oc}$.

Consequently, an increase in the cell temperature of 1 °C would result in decreasing the open circuit voltage to −2 mV. For our selected PV module (AEG PQ 10/40/01), which consists of 40 PV cells connected in series, an increase of cell temperature in summer (worst case in Palestine during July) of $\Delta T_c = 45\ ^\circ C$ would result in reducing the V_{oc} of the PV module (i.e. and the array) to:

$$\Delta V_{oc} = -(2\ mV/^\circ C) \times 40 \times 45\ ^\circ C = -3.6\ V$$

Therefore, at this condition, we would obtain from Fig. 3:

$$V_{oc} = 22.4 - 3.6 = 18.8 \text{ V}$$

and in worst case, the output voltage at the maximum power point (V_{mpp}) will be decreased by the same amount and becomes:

$$V_{mpp} = 17.5 - 3.6 = 13.9 \text{ V}$$

This means that selection of such a PV module (consisting of 40 cells connected in series) is very appropriate for such applications in Palestine, since its output voltage remains, even in the worst case (during extremely hot summer), higher than the nominal charging voltage of the battery (12 V).

3.2.2. The voltage regulator

The input voltage of the VR varies according to solar radiation intensity in the range from 0 to 22.4 V, while its output is adjustable from 10.8 to 14.4 V. To protect the battery against deep discharge, the VR disconnects the load from the battery when its voltage sinks to 10.8 V, and to protect it against overcharging (i.e. consequently gassing), the VR separates the battery from the PV array when its voltage reaches 14.4 V. The nominal power of the VR is usually selected to be equal to the peak power of the PV array (= 384 W).

3.2.3. The storage battery

The battery is indispensable for such PV power systems operating in stand-alone mode in rural areas. Lead acid battery cells with high cycle rate and capability of withstanding very deep discharge are the most appropriate type for PV systems. For the PV system of the clinic, the battery set should store enough energy to cover the load demands for a period of 3 days without the sun.

The necessary ampere hour (C_{Ah}) and watt hour capacity (C_{Wh}) are computable as follows [4,7]:

$$C_{Ah} = \frac{3E_{dl}}{\eta_B \times \text{DOD} \times V_B} \tag{11}$$

$$C_{Wh} = C_{Ah} \times V \tag{12}$$

where η_B is the battery efficiency and DOD is the permissible depth of discharge. Assuming realistic values of $\eta_B = 85\%$, DOD = 70% and $V = 12$ V, we obtain:

$$C_{Ah} = \frac{3 \times 1420}{0.85 \times 0.7 \times 12} = 597\text{A h}$$

To realize this capacity, six battery cells (type Anker, Norway) each rated at 12 V/105 A h were connected in parallel to the output terminals of the VR. In this case, the total C_{Ah} and C_{Wh} installed in the system became 630 A h and 7.56 kW h, respectively.

4. Test results, analysis and conclusions

The PV power system with the data acquisition system illustrated in Fig. 1 was built in a small clinic, where continuous measurements for two years had been carried out. In addition, a meteorological station employing an automatic data logger for the measurement of global solar radiation, ambient temperature, relative humidity and wind velocity was also built in the vicinity of the PV system. Fig. 4 illustrates the daily average of global solar radiation intensity measured on a horizontal surface at the project site during the two test years [3].

The solar radiation intensity on the PV array surface and consequently the input solar power (P_{sin}) are computable through Eqs. (6) and (7), respectively. The average daily energy output of the PV array (PV generator) and the consumption of the load through the months of the first and second test year are illustrated in Figs. 5 and 7, respectively.

The monthly totals of input/output ampere hour (A h) of the storage battery for the first and second test year are illustrated in Figs. 6 and 8, respectively.

The analysis of these test result leads to the following summarized conclusions:

(a) The energy produced by the PV array is higher in reasonable W h amount than the energy consumption of the load during the whole months of the first and second test years (Figs. 5 and 7, respectively). This means that the peak power of the PV array is appropriate and not oversized. Of course, the difference between the two kW h curves is stored in the battery.

(b) The load consumption is higher during the months May–September of the two test years due to increase of the ambient temperature, which results in lengthening the operation time of the refrigerator during this period. Based on measurements, the average daily energy consumption of the refrigerator during the nominated period is 1076 Wh/day, while its operation time is 16.53 h/day. In

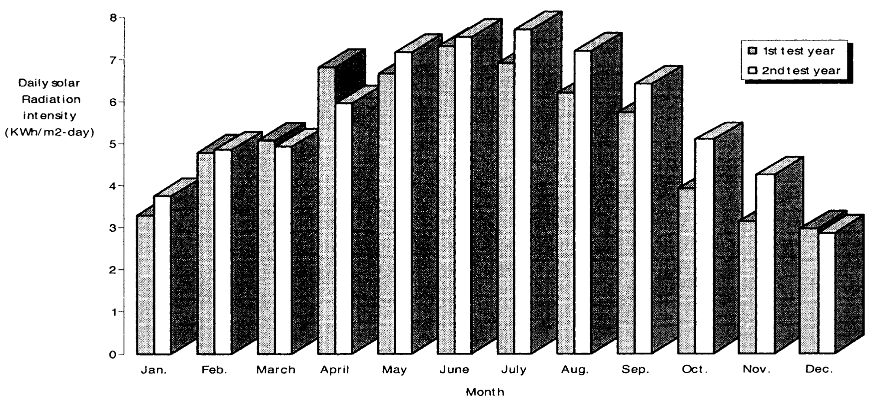

Fig. 4. Average daily solar radiation intensity measured on horizontal surface on project site in Palestine.

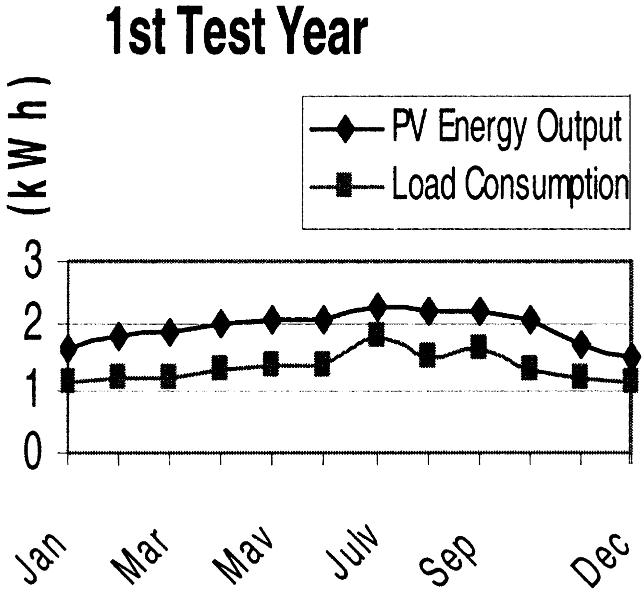

Fig. 5. Average daily energy output (kW h) of the PV array and the daily energy consumption of the load during the first test year.

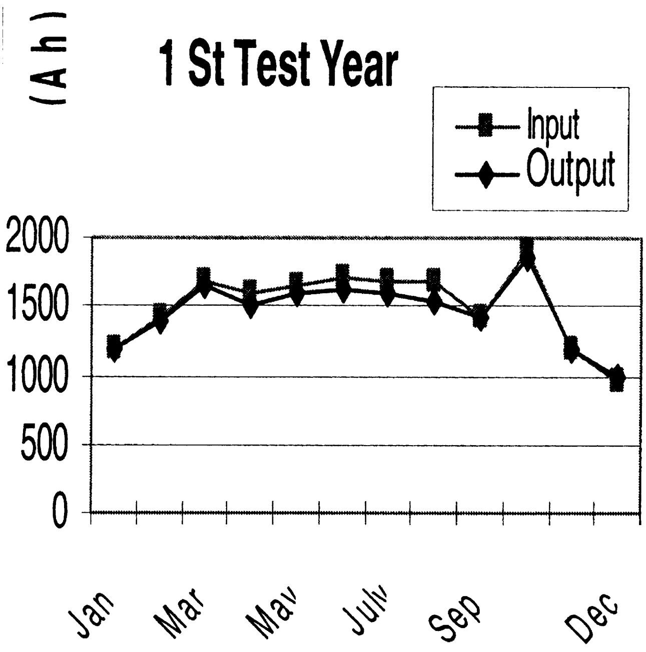

Fig. 6. Monthly battery A h-input/output during the first test year.

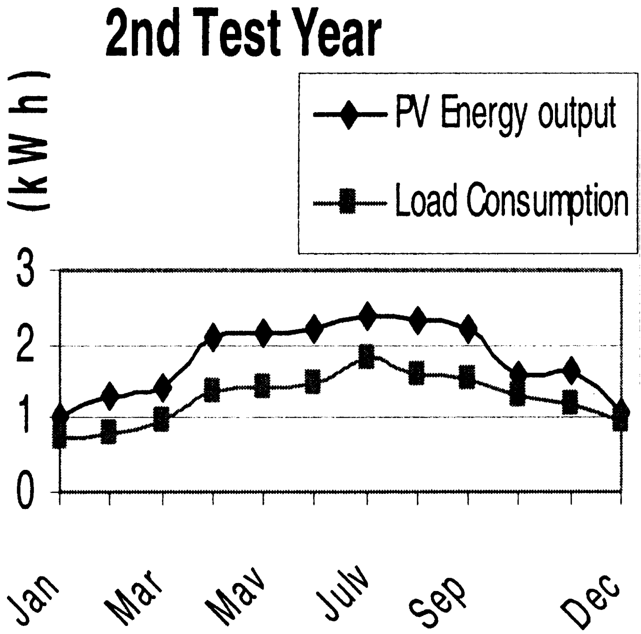

Fig. 7. Average daily energy output (kW h) of the PV array and the daily energy consumption of the load during the second test year.

both Figs. 5 and 7, it is obvious that the maximum load consumption coincides with July, when the ambient temperature achieves its maximum.

Fortunately, due to higher solar radiation intensity during the mentioned period (Fig. 4), the PV array generates higher power accordingly.

(c) Inspecting the input/output ampere hours (A h) of the battery during the first test year (Fig. 6), one finds that the (A h) input and output are equal during the seven months, September–March, when the solar radiation intensity is low (Fig. 4).

During the remaining months, the input (A h) is higher than the output (A h) which means that the PV array and the storage battery, with respect to variation of solar intensity along the year, are appropriately matched. The relations during the second test year are approximately similar (Fig. 8).

(d) During the months of extraordinary high solar radiation (>5.4 kW h/m^2 day), the PV array cannot deliver its full peak power (384 W) because the battery is fully charged and the load consumption during the sunshine hours is lower than this amount. This issue hinders the PV array from generating power at its peak efficiency, which was measured to be 7.7%.

(e) The total installed W h capacity of the storage battery, which is 7.56 kW h, is higher than the daily load demand in order to satisfy the daily energy requirement for sunless periods of 3 days. This is the reason why the battery is always

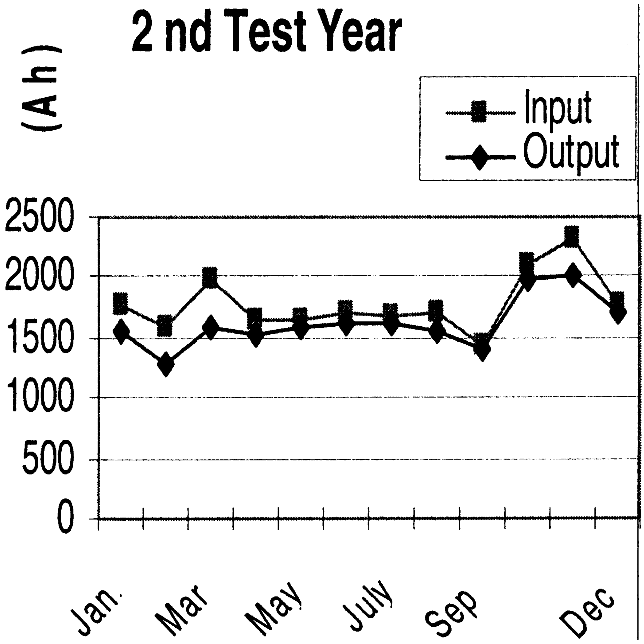

Fig. 8. Monthly battery A h-input/output during the second test year.

fully charged and consequently the PV array cannot work at its maximum efficiency.

(f) Extra tests on the characteristic of the PV array as a function of cell temperature had shown that the open circuit voltage and peak power of a PV module (consisting of 40 PV cells in series) decrease considerably with increasing cell temperature as −98 mV/°C and −0.194 W/°C, respectively.

According to the manufacturer data sheet, the NOCT of the used PV module type is 44 °C. Substituting this value in Eq. (10), the cell temperature in the PV module will be 75 °C if the ambient temperature and solar radiation intensity rise (at the same time) to 45 °C and 1000 W/m^2, respectively. In this case, the peak power of the module and array drops by −9.7 and −97 W, respectively. Therefore, special attention should be paid when designing PV power systems for utilization in countries with hot climates such as Palestine. Otherwise, the nominal charging voltage of the battery set or the targeted peak power may not be achieved during the hot periods.

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